A PECULIAR BELT OF OBLIQUE FAULTING

ROLLIN T. CHAMBERLIN
University of Chicago

The Rocky Mountain system is a belt of varying structure. Northward from northern Montana it is a sharply delineated chain bordered on its eastern margin throughout many degrees of latitude by great overthrust faults. But in central Montana the regular, linear, faulted chain loses much of its distinctiveness and gives way to an irregular group of scattered mountain clusters.[1] Farther south in Wyoming and Colorado the Rockies reassemble in a more definite continuous chain, but in these latitudes folding has replaced faulting as the dominant structure.

For the present paper it is important to note that in central and southern Montana the Rocky Mountain chain, which elsewhere constitutes the definite backbone of the continent, spreads out into a plexus of short minor ranges and isolated mountain groups. These reach far out into the Great Plains province, where each of the individual groups becomes essentially a unit by itself. Some have resulted from igneous outbursts, and exhibit the results of vertically acting forces fully as much as horizontal thrusting; others have arisen largely from faulting or folding. In consequence of this diversity of origin of the major features, the general region has been subjected to stresses of quite variable sorts. It is to emphasize the peculiar manifestation of some of these that the present paper is ventured.

From the vicinity of Billings, in the midst of this region of scattered uplifts, E. T. Hancock has recently described a very remarkable belt of faulting, some 56 miles in length and comprising over 90 separate faults, relatively close together and more or less parallel one to another.[2] A striking feature of the belt is that

[1] Rollin T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, XXVII (1919), pp. 147–48.

[2] E. T. Hancock, "Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geol. Survey*, Bull. 691-D (1918), pp. 101–47.

the fault lines, practically without exception, are inclined in the neighborhood of 45° to the long dimension of the faulted strip (Fig. 1). Many of these faults are over 5 miles in length, while one slightly curving fault plane has been traced for fully 10 miles. A few of the shorter faults, however, are less than a mile in length. As mapped by Hancock, these faults cut through a region surfaced by the Colorado and Montana groups of the Cretaceous, and by the Lance formation of the early Tertiary.

Hancock has clearly brought out the fact that the belt of faulting is located on the flanks of two conspicuous domes, which are the two dominating folds of the Lake Basin field. These are the Big Coulee–Hailstone dome in the northwest portion of the area studied, and the end of the Big Horn Mountain anticline, which extends into the southeastern corner of the Lake Basin field.[1] Southeast of the Big Coulee–Hailstone dome, in the direction of its principal axis, is a minor circular uplift which the author has called the Broadview dome. Hancock has pointed out the fact that the most intense faulting occurred along the steeply dipping south flank of the Big Coulee–Hailstone dome and around the southeast side of the Broadview dome.[2] From the Broadview dome to the northwest end of the Big Horn Mountain anticline very few faults were observed, but on the northwest slopes of the latter uplift they again become numerous. In short, the faulted strip follows the southern flank of the Big Coulee–Hailstone dome (including its satellite, the Broadview dome) and, after crossing an intermediate area where there are fewer faults, continues in nearly a straight line along the northern flank of the Big Horn uplift.

Both the doming and the faulting, which may perhaps be termed the local structural features of the Lake Basin field, are regarded by the author as in all probability related in origin to the major structures of the general region, and to have been determined more or less by the complex forces involved in the development of these major structures. "The mountain masses whose development has probably been the most active in determining the nature of the minor structural features in the vicinity of the Lake Basin field

[1] *Ibid.*, pp. 133–34.

[2] *Ibid.*, p. 136.

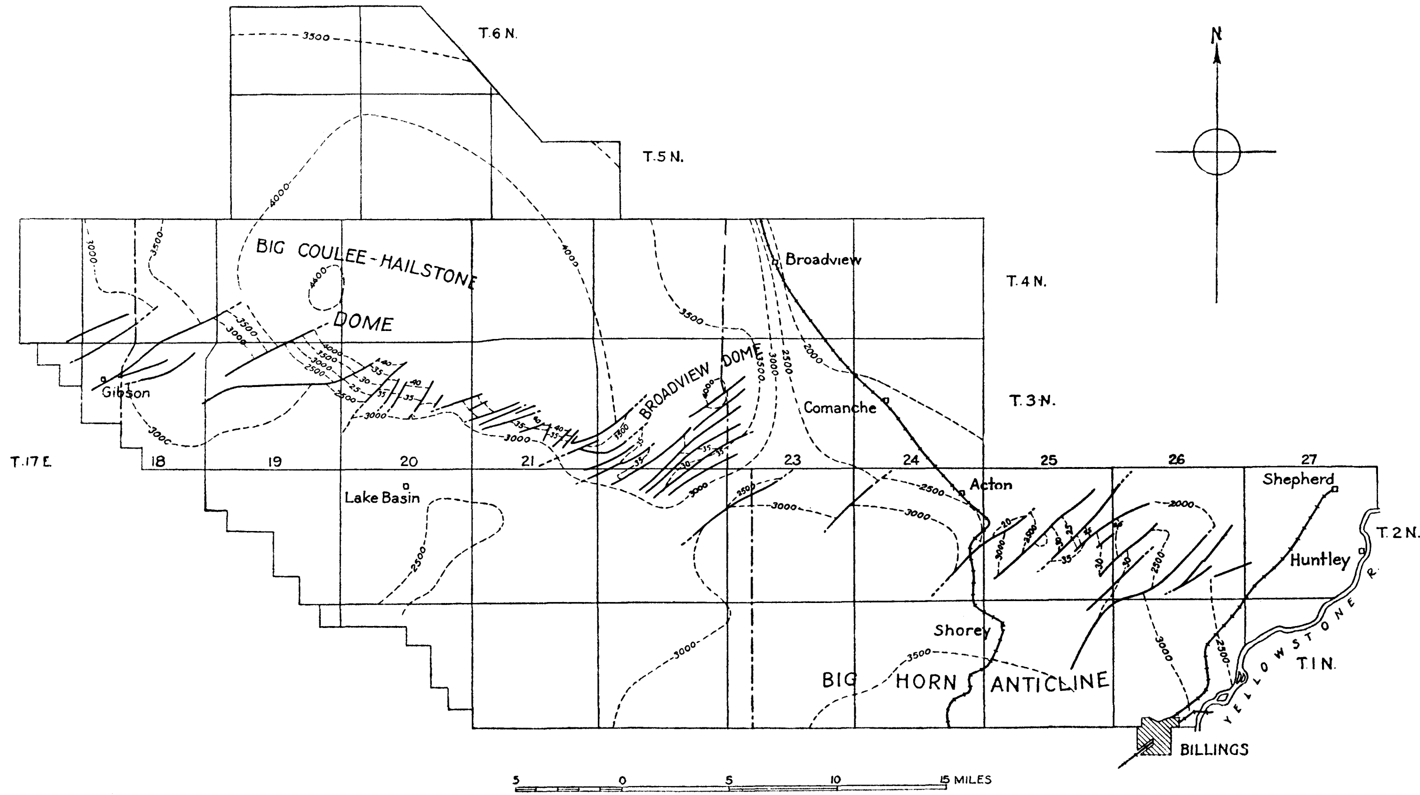

FIG. 1.—Map of the belt of faults in the Lake Basin field, Montana. The individual faults are inclined in the neighborhood of 45° to the long dimension of the belt. The dotted lines represent the structure contours on the base of the Eagle sandstone. Contour interval 500 feet. These contours depict the Big Coulee–Hailstone dome in the northwest portion of the area and the end of the Big Horn uplift in the southeast portion. (Redrawn from E. T. Hancock.)

are the Big Snowy Mountains on the north, the Little Belt Mountains on the northwest, the Snowy Range on the southwest, and the Big Horn Mountains on the southeast."[1] In three of these ranges the uplift has been so great that the pre-Cambrian complex is now exposed in the central core. Igneous outbursts have occurred in the general region, though not recognized within the Lake Basin field itself. The general setting of this remarkable faulting is admirably portrayed in this *Bulletin*, and many suggestive details are brought to the front, but as no definite explanation of the faulting is offered, I herewith venture to suggest some of the possible factors which may have given rise to the phenomenon.

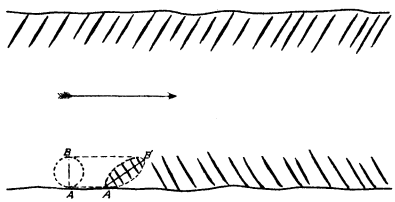

FIG. 2.—Diagram to illustrate the formation of oblique crevasses along the margins of a glacier moving in the direction indicated by the arrow. The crevasses point upstream as they extend toward the middle of the glacier where the motion is more rapid.

POSSIBLE EXPLANATIONS

There are two familiar processes which are known to produce parallel fracturing in a zone such as described. The first is illustrated by the development of oblique crevasses along the margins of valley glaciers. As the middle portion of a glacier moves more rapidly than the ice near the sides, a line on the glacier connecting points A and B (Fig. 2) will, after a time, become A′B′.[2] Since A′B′ is longer than AB, there has been stretching along that line. In fact, it can readily be shown that A′B′ represents the direction of elongation, or major axis of the strain ellipsoid, as developed by Leith.[3] Tension therefore develops along this line, and is relieved by fractures at right angles to it. Hence it is that the lateral margins of valley glaciers are commonly riven by a great

[1] E. T. Hancock, *op. cit.*, p. 132.

[2] John Tyndall, *Glaciers of the Alps* (1860), pp. 318–19.

[3] C. K. Leith, *Structural Geology* (1913), pp. 16–21.

It is of course to be recognized that, since the rate of motion changes more rapidly near the margin of the glacier than toward the middle, the line A′B′ will be curved instead of straight, and ideally the relation should be represented by many small strain ellipsoids instead of one large one.

succession of parallel crevasses which point obliquely upstream as they extend in toward the middle of the glacier. Such a belt of crevasses bears some resemblance to the belt of faults in the Lake Basin field.

The other process which is known to produce results of this kind is torsion. Its behavior has been strikingly illustrated by the familiar experiment of Daubrée, who subjected a long plate of glass to torsional stress.[1] The result was to produce numerous fractures in two distinct sets which crossed each other approximately at right angles (Fig. 3). The fractures of each set were nearly parallel to one another, and were inclined approximately at 45° to the axis of torsion. Either set of parallel fractures would look much like the strip of faults in the Lake Basin field, provided the other intersecting set did not form.

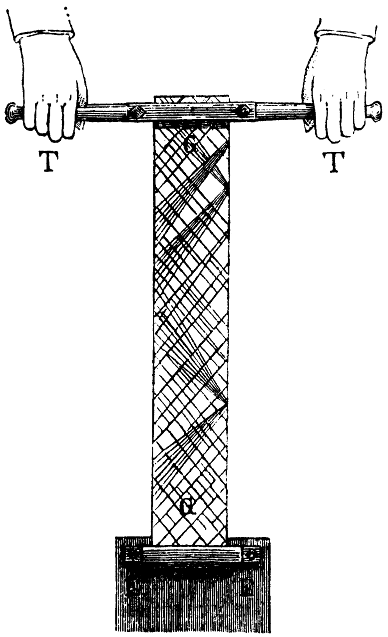

FIG. 3.—Fractures developed in a glass plate by torsion. The two sets of fractures are nearly at right angles to each other and inclined 45° to the axis of torsion. (From Daubrée.)

APPLICATION TO THE LAKE BASIN FAULTING

The most striking characteristic of this belt of faulting in Montana is the grouping of the faults in a long, narrow strip trending W.N.W. and E.S.E. Scarcely less conspicuous is the fact that, almost without exception, the individual fault traces are inclined to the axis of the belt at angles in the general vicinity of 45°. The third fact of prime significance appears to be that toward the west end of the belt the fracturing took place on the south flank of an uplifted tract, while toward the east end of

[1] G. A. Daubrée, *Études synthétiques de géologie expérimentale* (1879), Tome 1, pp. 307–15.

the belt the fracturing has occurred on the north flank of another distinct uplift. In the area between the two uplifts there has been some but noticeably very much less faulting than on the immediate flanks of the two uplifts. In the process of doming, the strata near the west end of the faulted strip were uplifted on the north and given a southerly tilt, while near the east end of the zone of faulting the strata were uplifted on the south and thus given a northerly tilt. Thus the two ends of the faulted area were tilted in opposite directions. Such an opposite movement involves a certain amount of twisting, or torsion. The axis of the twist would coincide with the long axis of the present fault belt. If the strains developed in this adjustment between the oppositely tilted areas were sufficiently great, they would produce fracturing along planes inclined approximately 45° to the axis of torsion, or long dimension of the present faulted belt. Daubrée's experiment would suggest that these fractures should occur in two sets crossing each other at right angles. One such set, to the number of more than 90 faults, is in just the position to meet the requirements, but the complementary set, with the exception of two very short faults northeast of the Broadview dome, is lacking.

The explanation of the failure of the cross-fractures to open is sought in the trend of the axis of torsion, whose general direction hovers around N.80°W. The fractures of the set which actually did form have a N.E.-S.W. trend. If the complementary set of fractures had developed, they also should have opened in planes inclined 45° to the axis of torsion and at right angles to the first set, which would place them in the neighborhood of N.35°W. It will be observed that this last figure is not far from the general trend of the adjacent portion of the Rocky Mountains. The Rocky Mountains owe their formation, for the most part, to compressive stress. While the exact stress-strain relations involved in the development of this portion of the Rocky Mountains are not known with certainty, it is, however, certain that an effective component of compressive stress (whether the strain were rotational or non-rotational) has operated at right angles to their long dimension, and so also in a direction at right angles to the postulated possible cross-fractures. Hence any such N.W.-S.E. fractures,

which might otherwise have developed in response to the local tension developed by the torsion, might be prevented from forming by the Rocky Mountain compressive stresses, provided the torsion came at a time when the Cordilleran compressive stresses were still operative. This would not seem an unreasonable assumption since the Rocky Mountain province has been subjected to such stresses during much of Cenozoic time.

But, according to Becker, if faulting takes place because of torsion, the faults should be inclined in the same sense as the thread of a right-handed screw, when the twisting has been clockwise, as it seems to have been in the Lake Basin field case.[1] This would be in consequence of the nature of the strain at or near the surface of the earth. There the direction of elongation should be N.E.-S.W. and fracturing on this principle should occur along lines trending N.W.-S.E. On the other hand, an analysis by the strain-ellipsoid method shows that if a body having two parallel sides, like Daubrée's glass plate, be twisted, the axes of strain on the opposite sides are exactly reversed. In Daubrée's experiment both sets of torsion fractures were about equally developed. This was because the strains developed on the two faces of the glass plate were about equally effective in causing the fracturing of the plate.

For confirmation of these principles, paraffine was molded into strips having the dimensions $12 \times 2 \times \frac{1}{2}$ inches. The ends of these strips were then twisted clockwise as in the Lake Basin case. Each strip snapped apart along a single fracture surface. The fracture in 10 different tests was in accordance with the orientation observed in Montana. In 11 tests it was contrary, the fracturing belonging to the cross set. In every test, without exception, the fracture occurred not far from 45° to the axis of torsion. These tests would seem to indicate that in strips, or plates, of the sort used, neither set of fractures takes real precedence over the other in forming. But in the earth the underside of the paraffine block finds no exact counterpart, and the strain conditions on the upper surface should dominate. Hence, other things being equal, there is greater likelihood that the right-hand-screw fractures

[1] G. F. Becker, "The Torsional Theory of Joints," *Trans. Amer. Inst. Min. Eng.*, XXIV (1894), pp. 130–38.

will be produced. This would be the set at right angles to those actually occurring in the Lake Basin field.

Becker has also stated that, if due to torsion, each master fault will be a reverse fault, and the fissures will gape from the start.[1] Examination of the fracture planes in the paraffine tests revealed the fact that many of them were straight across or, expressed in terms of structural geology, were vertical faults. In others the fault surface was somewhat inclined from the vertical, or was vertical for a portion of the distance and then curved. Where the fault plane was inclined from the vertical the relations were, as Becker has stated, those of a reverse fault. The hanging wall was elevated with respect to the foot wall. The paraffine tests also confirmed Becker's statement that the fissures will gape. This does very well in an experiment where the weight of materials plays no important part. But reverse faults which gape would be a curiosity in the earth. While in the earth, just as in the experiment, the twisting would tend to cause this relation, on the other hand the gravity of the earth, in co-operation with the tension developed by the torsion, should offset this tendency. If the twist developing such a series of parallel faults were accompanied by much tension, downsliding of the blocks should be expected. As there seem to be special grounds for expecting tension, independently of the torsion, in the case under consideration, reverse faulting as the dominant type in this particular strip in Montana would seem unlikely.

Furthermore the strains developed by the doming process above outlined would, in all probability, not be of a very intense sort unless there were also counterpart downwarping north of the Big Horn uplift and a depression of the basin south of the Big Coulee–Hailstone dome to complete the twist. Some depression of the basins seems likely, but the twisting was probably not violent. Hence the fracturing, so far as due to torsion alone, should be not far from vertical, and the tendency toward reverse faulting would be slight. Nevertheless in this connection it is interesting to note that reverse faults actually do occur in one section of the fault belt under consideration.[2] Normal faulting, however, dominates.

[1] G. F. Becker, *op. cit.*, p. 137.

[2] E. T. Hancock, *op. cit.*, p. 140.

From the foregoing inspection of the problem, it would seem clear that this remarkable strip of oblique faults has not been produced by simple torsion alone. The observed facts are at variance in several essential particulars with what the theory of pure torsion should require. The genesis of the faults must have involved in addition other important factors. These are to be sought in an analysis of the larger structural features of the general region, and a consideration of the strains involved in their genesis.

A study of the map of Montana shows that, while the Rocky Mountain chain loses much of its regularity and individual linear character amidst the scattered mountain groups of west central Montana, there is nevertheless a prominent Rocky Mountain trend line which swings sharply eastward in southern Montana, and thence turns south again in the Big Horn range. This particular line of the Rockies thus follows a sigmoidal curve which is perhaps more conspicuous on a small-scale map than a map of a larger scale, for the reason that the details of the minor ranges, if they are too prominent, tend to obscure the larger relations. It was suggested by T. C. Chamberlin that this pronounced bend in the range may have been an important factor in the present problem. The great Lewis overthrust of northern Montana shows that the Glacier National Park region has been transported bodily eastward for at least 15 miles, and possibly much farther.[1] Southward from Glacier National Park the easterly overriding upon the thrust plane gradually diminished, but in any case, even where the faulting has given way to folding as the dominant process, the formation of the Rocky Mountain structure involved an eastward movement of the crumpled and faulted materials. To accomplish the crustal shortening involved in the folding, the main mass of the Big Horn Mountains should have moved eastward to some extent, on the assumption that the deformation was due to thrusting from the Pacific.

The northwestern extremity of the Big Horn anticline, as already stated, extends into the southeastern corner of the area under consideration. Thence westward to the Crazy Mountains

[1] M. R. Campbell, "The Glacier National Park," *U.S. Geol. Survey*, Bull. 600 (1914), p. 12.

the system is poorly developed. This poorly developed tract lies on the border of the eastward-trending portion of the Rocky Mountain belt, which connects its overthrust tract in northern Montana with its south-trending tract in Wyoming and Colorado. Because of its general east-west trend, it was not in a position to be much folded by a thrust from the Pacific, but on the contrary was well placed to receive elongation from the greater eastward thrust of the Rocky Mountains farther to the south. The Big Horn Mountains seem to partake in some measure of both these attitudes, for the southern portion trends with the Rockies in Wyoming and Colorado, while the northern portion veers round to a more westerly trend, and dies down in the Lake Basin district on the very border of the fault belt which, in striking eastward from the Big Coulee–Hailstone dome, is almost tangent to the northern flank of the range.

From these relations it will be seen that, though the deformation on the border of the Lake Basin was limited and gentle, there would naturally have been some eastward movement at the Big Horn end. On the other hand, the Big Coulee–Hailstone dome at the northwesterly end lay on the Great Plains side of the fault belt, in the lee of the less-moved portion of the Rocky Mountain belt, and appears also to be more nearly related to the group of igneous intrusions than to the folded belts, and so should have been less affected than the Big Horn end by the eastward movement. Hence it is inferred that the southern portion of the Lake Basin field, which was most influenced by the Big Horn deformation, was shifted eastward, while the northern portion partook rather more of the relative fixity of the Great Plains province and the area of igneous intrusions. The differential motion involved in this adjustment is not unlike that which produces the oblique crevasses along the margins of glaciers, except that the differential movement was distributed, instead of having a limit at a sharp borderline of slippage such as lies at the junction of the moving glacier with the wall of the valley. No such line of sharp differentiation is of course assignable to the rather broad and gentle movements in the Lake Basin. There may of course have been a concealed longitudinal shear plane deep below the fault

belt, but as the map shows only small oblique faults, this supposition has little or no tangible support and need not be seriously considered here, as the movements already discussed would still be needed to explain the oblique faults. If any underlying longitudinal fault is to be postulated, a group of such faults with distributive action would best fit the case.

On the glacier principle, the southern portion of the district, moving eastward relative to the northern portion, should cause repeated crevasse-like fractures to open along a belt where the strain from the differential motion was greatest. As the south side of the belt moved eastward with respect to the northern side, tension would be developed along N.W.-S.E. lines obliquely across the disturbed zone. The result would be a large number of fracture lines at right angles to the direction of tension, or running N.E. and S.W., as in the upper part of Figure 2. The oblique crevasses in a glacier point upstream as they extend toward the middle of the glacier, or toward the more rapidly moving portion. Hence in this fault problem the fractures should be inclined toward the direction from which the relative motion came. This is just what was observed in the faulted zone of the Lake Basin field. It is then only necessary to suppose that the zone of yielding between the differently moving areas was located where the faults have developed.

Near the eastern end of the fracture belt the downthrow side of nearly all of the faults is toward the northwest. As these are normal faults, most of the fault planes dip to the northwest. On the other hand, near the western end of the belt the downthrow side, and hence also the dip, of the majority of the fault planes is toward the southeast, though the faulting is less regular at this end than at the other. The downslipping in general has thus been from the ends toward the middle of the belt, though the generalization is not so well substantiated in the western half flanking the Big Coulee–Hailstone dome as it is in the more regular eastern half bordering the Big Horn uplift. The dome at either extremity represents a relative upthrust which, if the result of igneous activity beneath, necessarily adds a further element of tension, thus favoring an increase in the number of fractures upon

the flanks of the domes, while at the same time it tends to give the observed slopes to the fault planes.

This peculiar belt of oblique faulting is therefore attributed to the eastward movement of the southern portion of the region relative to the northern, together with the local torsion and incidental tension developed by the doming process.